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20.0 STRESS ANALYSIS

20.1 INTRODUCTION

This section outlines the basic stress analysis design criteria, and design procedures established to ensure the fundamental safety and structural integrity of the gas pipeline. Applicable regulations, codes, and criteria pertaining to stress analysis are presented. The types of loads, loading conditions, and combinations of loads are identified and discussed. The basic design criteria for acceptable levels of stress and strain in the pipe are established for all identified loading conditions. The appropriate methods and procedures of analysis to be used in the final design are subsequently defined.

20.2 CODES AND CRITERIA

20.2.1 Codes

- Code of Federal Regulations, Title 18 – Conservation of Power and Water Resources
- Code of Federal Regulations, Title 49 - Transportation, Part 192, Transportation of Natural and Other Gas by Pipeline: Minimum Federal Safety Standards.
- Federal Right-of-Way Grant for the Alaska Natural Gas Transportation System Alaska Segment, Serial No. F-24538 (December 1, 1980), as such may be updated and/or amended from time to time
- American Society of Mechanical Engineers, "Gas Transmission and Distribution Piping Systems," ASME B31.8, latest edition.
- American Society of Civil Engineers, "Minimum Design Loads for Buildings and Other Structures", SEI/ASCE 7-02.
- American Petroleum Institute, "Recommended Practice for Railroad Transportation of Line Pipe," API 5L1, 5th edition.
- American Institute of Steel Construction, Manual on Steel Construction ASD (Allowable Stress Design), 9th edition
- American Institute of Steel Construction, Manual on Steel: Load and Resistance Factor Design-LRFD, 3rd edition
- American Concrete Institute, Building Code Requirements for Structural Concrete, and Commentary, ACI 318-02/318R-02
- American Petroleum Institute, "Recommended Practice for Transportation of Line Pipe on Barges and Marine Vessels," API 5LW, 2nd edition.
- Federal Energy Regulatory Commission conditional certificate of public convenience and necessity, issued on December 16, 1977, as such is finalized

20.2.2 Criteria

20.2.2.1 Maximum Allowable Stress Levels

The maximum allowable stress levels calculated on an elastic basis will be as follows:

1. Hoop Stress from Design Operating Pressure (49CFR192)

Class Location	Allowed Stress
1	0.72 SMYS
2	0.60 SMYS
3	0.50 SMYS
4	0.40 SMYS

2. Combined Membrane Stress in Buried Restrained Pipe

• Stress intensity from design pressure and temperature differential	0.90 SMYS
• Stress intensity from design pressure, temperature differential, and design operating earthquake	1.00 SMYS
• Stress intensity from design pressure, temperature differential, and design contingency earthquake	1.10 SMYS

3. Confined Membrane and Bending Stress in Buried Restrained Pipe

• Stress intensity from design pressure, temperature differential, and circumferential bending stress due to overburden or longitudinal bending stress due to buoyancy	1.00 SMYS
• Stress intensity from design pressure, temperature differential, design contingency earthquake and circumferential bending stress due to overburden or longitudinal bending stress due to buoyancy	1.15 SMYS
• Maximum effective stress from test pressure, test temperature differential and circumferential bending stress due to overburden and wheel loads	1.10 SMYS
• Circumferential bending stress due to overburden and hoop membrane stress	0.90 SMYS

from design pressure or zero gage pressure	
• Circumferential bending stress due to overburden and wheel loads and hoop membrane stress from design pressure or zero gage pressure (uncased road crossings)	0.80 SMYS

4. Combined Longitudinal and Torsional Stress in Aboveground Pipe (ANSI B31.8)

• Expansion stress from temperature differential (longitudinal bending stress combined with torsional stress)	0.72 SMYS
• Expansion stress from temperature differential, longitudinal membrane stress from design pressure, and longitudinal bending stress from operating dead load, snow/ice load and wind load	1.00 SMYS
• Longitudinal membrane stress from design pressure and longitudinal bending stress from operating dead load, snow/ice load, and wind load	F (0.75) SMYS where F is the Design Factor for the Class Location

- 5. Combined Membrane and Longitudinal Bending Stress in Aboveground Pipe

• Stress intensity from design pressure, temperature differential operating dead load, wind load, and snow/ice load	0.90 SMYS
• Stress intensity from design pressure, temperature differential, operating dead load, and design operating earthquake	1.00 SMYS
• Stress intensity from design pressure, temperature differential, operating dead load, and design contingency earthquake	1.10 SMYS
• Stress intensity from test pressure, test temperature differential, and test dead load	1.10 SMYS

20.2.2.2 Maximum Allowable Strain Levels

For buried pipe, combined longitudinal membrane and longitudinal bending strains will be calculated by nonlinear analysis with consideration of movement in the supporting soil. For design purposes, the allowable maximum longitudinal strain is determined by using the methodology outlined below.

20.2.2.2.1 Allowable Compressive Strain

The following approach will be utilized for the compressive strain limit criteria:

- The compressive strain limits is based on the local buckling strain, which represents the initiation of local buckling and is defined at the peak load point on a load-displacement curve. For a pipeline subjected to displacement-controlled loads, the initiation of local buckling is not a containment failure condition because of the inherent stability in the displacement-controlled loading process in the post-buckling regime. The factor of safety against containment failure will consequently be much larger than the factor of safety against the initiation of local buckling.
- Supplemental validation of the predicted compressive strain limit can be provided by local buckling tests when project specific pipe materials and/or sections are available.
- Since the compressive strain limits are established based on maintaining the pipeline functionality, rather than the pipeline failure condition, the compressive strain limit safety factor will be 1.0 for geohazards.

20.2.2.2.2 Allowable Tensile strain

The following approach will be utilized for the tensile strain limit criteria:

- The pipe grade and wall be specified to meet the requirements of API-5L or CSA Z245.1 and additional company specifications.
- Company specifications will provide for requirements on the chemistry of the pipe, requirements on the toughness of the pipe, limits on the range of the yield strength and on the Yield to Tensile ratio.
- Additional “for information only” requirements will be placed on the pipe specification to provide the longitudinal yield stress in addition to the normal hoop stress specification.
- Mechanized Gas Metal Arc welding will be specified where appropriate for the project. The welding qualification will have requirements to measure the Charpy and CTOD toughness as well as the weld metal yield and ultimate strength.
- Mechanized ultrasonic inspection will be specified for the weld inspection.
- Defect acceptance criteria will be based on an engineering approach validated through wide plate tests on project pipe.
- The tensile strain limit will include a safety factor of 1.5

20.2.2.3 Maximum Allowable Stress Levels for Transportation and Stacking

1. Circumferential bending stress during rail or truck transport (API RP-5L1) 0.30 UTS
2. Circumferential bending stress during marine transport (API RP-5L5) SMYS/(1+g)

   where g is taken as 0.4 unless recommended higher by shipper

3. Circumferential bending stress during yard stacking 0.50 SMYS

20.2.2.4 Maximum Allowable Pipe Ovalling

The maximum allowable decrease in pipe diameter resulting from overburden and wheel loading will be 5 percent of the pipe diameter ($\Delta x < 0.05D$).

20.2.2.5 Elastic Stability

Pipeline sections subjected to axial compression loadings will be checked for column buckling in accordance with the Euler formula. The maximum unsupported span will be limited to 80 percent of the calculated critical buckling span considering appropriate boundary conditions.

20.2.2.6 Seismic Design Criteria

The seismic design is in accordance with the Project Seismic Criteria. The values outlined herein are discussed in detail in the report "Seismic Design Criteria for the Alaska Segment of the ANGTS," April 1981 and "Addendum-Seismic Design Criteria for the Alaska Segment of ANGTS," February 1982. The criteria will be updated to incorporate current seismic characterization.

1. Design Contingency Earthquake (DCE) - Horizontal Ground Motion
   - The effective horizontal ground motion used to determine the buried pipeline response is shown in Table 20-1.
   - The horizontal shear wave propagation velocity (Cs) that will be used with the preceding data is:

C_S (ft/sec.)	Material
3,000	Rock or Thick Permafrost areas
2,000	Other areas

   - The effective horizontal ground motion used to determine the structural response of the aboveground pipeline with its supports is shown in Table 20-2.

2. DCE - Vertical Ground Motion

The effective vertical ground motion used to determine the response of either the buried pipeline or the above- ground pipeline with its supports will be two-thirds of the value used for the respective horizontal ground motion.'

3. Design Operating Earthquake- (DOE) Vertical or Horizontal Ground Motion

The effective ground motion for the Design Operating Earthquake will be 40 percent of the respective value used for the DCE.

20.3 DESIGN PROCEDURES

20.3.1 Design Approach

The following general design approach has been established to ensure the structural integrity of the pipeline:

1. Identify the loading conditions and establish the range of design loadings and geotechnical conditions to which the pipeline may be subjected during construction and operations. The effects of the following will be considered directly in stress analysis:
   - Internal pressure
   - External pressure from overburden
   - Pipeline temperature changes
   - Dead load of pipe, the pipe's contents (test water or gas), pipe coating, insulation and/or concrete coating or weight
   - Settlement
   - Frost heave
   - Buoyancy in saturated soils
   - Seismic ground motion
   - Construction loads
   - Wind load
   - Snow and ice loads
2. Select the minimum required pipe wall thickness in accordance with 49CFR192 based on Maximum Allowable Operating Pressure (Design Pressure).
3. Establish critical pipe material behavior and acceptable levels of stress and strain.
4. Perform elastic analyses of the buried pipeline for primary loads and secondary loading conditions which produce membrane stresses to verify the acceptability of combined stress levels. Perform additional nonlinear analyses to consider the effects of secondary stress and strain produced in the pipe as the result of movement of the supporting soils caused by forces at bends, differential settlement, frost heave and seismic motion.
5. Perform elastic analyses of the segments of pipeline which are aboveground for all applicable loading conditions to establish requirements for structural supports and design configurations so as not to exceed the limits of the design criteria.

20.3.2 Classification of Loading Conditions

The loadings are classified as to their effect on stress and strain as either primary or secondary. Definitions of primary and secondary stress vary between codes and are not specifically stated in 49CFR192. The project definitions are as outlined below:

- A primary load is a load which is not self-limiting and cannot be relieved by yielding or distortion. Primary loads on a pipeline include internal pressure and dead load of the pipe and its contents.
- A secondary load is a load which is self-limiting and can be relieved by yielding or distortion. Such a load is caused by movement of supports, restraint of adjacent parts, or self-constraint of the structure. Secondary loads on a buried pipeline include the effects of temperature changes, the effects of earthquake and the effects of movement of the surrounding soil media caused by displacement at bends and differential settlement or frost heave.

The conditions for which the pipe design is analyzed are classified as follows:

- Transportation loads are those imposed during handling, loading, stacking and shipping of the pipe.
- Construction loads are loads resulting from construction traffic.
- Pre-Operation loads include settlement that may occur after installation, and during the hydrostatic testing.
- Design operating loads are the sustained loads imposed by normal operations of the pipeline, the live load imposed by internal cleaning or inspection devices (pigs), and the maximum expected loads resulting from movement at bends, settlement, frost heave and design operating earthquake.
- Design maximum loads (contingency loads) include design operating loads combined with occasional loads such as loads from extreme conditions with a low probability of occurrence during the lifetime of the pipeline.

20.3.3 Design Loads

The design loads to be considered for the pipeline analysis and design are included in the following sections.

20.3.3.1 Internal Pressure

Internal pressure is a primary load which induces primary circumferential tensile stress and strain in the pipe wall by expanding the pipe radially. If the pipe is unrestrained, pressure also induces axial tensile stress by expanding the pipe longitudinally. Once buried, the pipeline is restrained and axial tensile stress develops as a result of Poisson's effect. Where changes occur in pipe alignment, internal pressure induces secondary longitudinal bending stresses. Internal pressure governs the required pipe wall thickness in accordance with the requirements of 49CFR192.

For a given operating pressure, the wall thickness required to meet this limitation is calculated using Barlow's formula in the following form:

$$t = PD/[2S\ (F \times E \times T)] \qquad (20.1)$$

Where:

t = Pipe wall thickness, in

P = Design operating pressure, psig

D = Pipe outside diameter, in

S = Specified minimum yield, psi

F = Design factor

E = Longitudinal joint factor

T = Temperature derating factor

The factor F is determined by Class location in accordance with 49CFR192.111.

The factors E and T are determined in accordance with 49CFR192.113, and 192.115, respectively, and are equal to 1.0.

The component of hoop stress resulting from internal pressure is determined using Barlow's formula as presented below:

$$S_h = PD/2t \qquad (20.2)$$

Where:

S_h = Hoop stress, psi

P = Internal pressure, psig

D= Outside diameter, in

t= Pipe wall thickness, in

In the unrestrained condition, longitudinal stresses are defined by the product of the internal pressure and the area of the pipe divided by the area of the steel.

$$S_L = A_P\ P/\ A_s \qquad (20.3)$$

Where:

S_L = Longitudinal stress, psi

A_P = Internal area of the pipe, in^2

P= Internal pressure, psig

A_s= Area of pipe steel, in^2

In the restrained condition, longitudinal stresses are defined by the product of Poisson's ratio and the hoop stress:

$$S_l = \mu PD/2t \qquad (20.4)$$

Where:

μ = Poisson's ratio, 0.3

20.3.3.2 Differential Temperature

The buried pipeline will be partially or fully restrained from expansion or contraction by the backfill and surrounding soil medium. Any change in temperature of the pipe steel after installation will induce secondary longitudinal stress. A change in temperature during operation or testing will induce either compressive or tensile membrane stress. The elastic analysis for buried pipe considers full restraint at maximum positive and negative temperature differential.

Longitudinal membrane stresses caused as a result of the temperature differential in the fully restrained pipeline are defined by:

$$S_1 = E(-\alpha)\,(T-T_i) \qquad (20.5)'$$

Where:

S_1 = Longitudinal stress, psi

E= Steel modulus of elasticity, psi

α = Steel coefficient of thermal expansion in/in/°F

T = Temperature in question, °F

T_i= Installation temperature, °F

In unrestrained aboveground segments of the pipeline, the thermal expansion and contraction produces longitudinal force and induces secondary longitudinal bending stress at bends, offsets, and sup- ports. The design temperature differentials will be input into an elastic analysis in combination with other applicable loads.

20.3.3.3 Dead Loads

Dead loads include the weight of the pipe, its contents and externally applied loads such as insulation system, concrete coating, concrete weights, or soil overburden.

The weight of the frost bulb, if any, acting on the pipe as determined by the geothermal analysis will also be considered as dead load.

The weight of the backfilled soil over the pipe is a primary load, bearing on the upper surface of the pipe and inducing a circumferential bending stress in the pipe wall. In areas where settlement may occur or in areas where the ditch bottom profile will not provide uniform support to the pipe, the overburden load may induce longitudinal stresses and strains in the pipe prior to operations.

The case of settlement is analyzed in accordance with Subsection 20.2.7. In cases where the construction specifications allow non-uniform support of the pipe or in site specific locations where actual support conditions are determined, the residual longitudinal strain from overburden loading will be included in determining the total longitudinal strain for comparison with the criteria allowables. The residual strain will be calculated as the strain resulting from the bending moment in the unpressurized pipe caused by the weight of the overburden extending over a span equal to the allowable unsupported length of pipe.

The effect of buoyant uplift on the buried pipe will also be considered as a dead load. Buoyant uplift can occur in areas where the pipeline is partially or fully submerged in water or saturated soil-water medium. Seismic activity may also cause a buoyant effect in certain liquefiable, soils.

20.3.3.4 Overburden and Vehicular Loads

The weight of the backfill above the buried pipe will deform the pipe and induce a circumferential bending stress in the pipe. The overburden load may be conservatively taken as equal to the weight of soil prism above the pipe:

$$W = \gamma HD \qquad (20.6)$$

Where:

W = Overburden load, lb/linear ft

γ = Backfill unit weight, pcf

D = Pipe outside diameter, ft

H = Height of fill above the top of the pipe, ft

Additional load will be transmitted to the pipe at highway crossings from vehicular traffic. Applicable wheel loads which have been factored for impact will be applied as a surcharge to the pipe in addition to the overburden. Determination of the total load W for use in equations will be made as follows:

$$W = W_0 + W_s \qquad (20.7)$$

Where:

W_0 = Appropriate overburden load

W_s = Surcharge Load due to the applied wheel loading

Where appropriate, more detailed analysis may be performed at road crossings.

In certain site-specific locations where detailed soils data are available, the overburden load may be calculated with consideration of the arching effect.

- Pipe Deformation and Stress

  The deformation and circumferential stress response of the pipe to the combined effects of the overburden and design vehicular loads are functions of the backfill load, the properties of the pipe, and the properties of the soil around the pipe. The resulting deformation and circumferential stress will be calculated considering the effect of the load transmitted through the subsurface to the pipe using conservative or site-specific soil mechanical properties, and the pipe mechanical properties. Analysis may be concluded though accepted manual calculations, e.g. Spangler, or by appropriate finite element analysis. The detailed calculations will be contained in the final design package.

20.3.3.5 Snow, Ice and Wind Loads

The aboveground segments of the pipeline will be subjected to loading from snow, ice and wind. These produce longitudinal bending stresses which will be considered primary loads.

20.3.3.6 Earthquake Loads

Earthquake activity induces stress and strain in the gas pipeline as a result of seismic ground shaking or fault displacement.

In the buried pipeline, propagating seismic waves induce strain in the pipe causing relative displacements along its length and the resulting membrane and bending stresses are considered secondary. It has been determined that the controlling design condition is the condition that induces the maximum longitudinal membrane strain in the pipe. This is calculated from the following equation:

$$\varepsilon_a = V/2C_S \qquad (20.8)$$

Where:

ε_a = Maximum longitudinal membrane strain, in/in

C_S = Minimum seismic shear wave propagation velocity, ft/sec

V = Maximum soil particle velocity, ft/sec

The axial strain as computed above may be conservative if slipping between the pipe and soil occurs. If slipping occurs, the maximum axial strain in the pipe is:

$$\varepsilon_a = f\,V/2C_S \qquad (20.9)$$

Where f is the reduction factor (f<l) to account for the slippage effect. Present analysis uses a value of 1.0 for "f." The criteria have been written to permit lower values if conditions require it. Appropriate justification will be provided for any lower value used in final design. In no case will "f" be less than 0.5.

For the aboveground sections of pipeline (such as river crossings) and its support system, the reference earthquake ground motions are in the horizontal plane, and the effects of vertical ground motion will be considered as being equal to two-thirds of the horizontal. These ground motions will be applied to produce the maximum effects on the pipeline and its supports. Response spectra from seismic criteria report will be used for the analyses, and the resulting membrane and bending stresses will be considered primary.

20.3.3.7 Load Values

Design load values will be as outlined below:

1. Internal Pressure and Test Pressure - in accordance with the project design basis.
2. Design temperature limits for thermal stress analysis are as follows (degrees Fahrenheit)

	Maximum	Minimum
Post backfill /Pre-hydrotest[1]	50	0
Test Media	50	32
Operating	40	0

3. Dead Load:
   - Steel weight as calculated from design thickness for each class location using nominal wall thickness, including insulation and jacketing weight as required
   - Maximum Gas Weight Test = 80 lb/ft
   - Test Water Weight = 62.4 lbs/ft^3
   - Overburden (maximum unit weight) = 135 lb/ cu ft
   - Maximum Pig Weight = 5000 lbs (may be varied in final design)
   - Maximum Frost Bulb Unit Weight for Use in Settlement Analysis = 110 lb/ cu ft
   - Concrete Weight (for weighting) = 150 lbs/ cu ft
4. Snow/Ice = 86 lb/ft
5. Wind Velocity = A maximum design wind velocity of 100 miles per hour. A refined value of wind velocity, attack angles, gusting and flutter considerations will be derived on a site-specific basis and in accordance with applicable ASCE 7 wind specifications.
6. Vehicular Wheel Loads (at crossings) 50-Ton Off-Highway Truck, End Dump
7. Earthquake (Buried Pipeline)

   The strains to account for the seismic wave propagation effects are computed using the particle velocity (v) values as shown in Table 20-1 using the appropriate minimum seismic shear propagation velocities.
8. Earthquake (Aboveground Pipe)

   Effective horizontal ground motion to determine structural response of aboveground pipeline and its supports for design contingency earthquakes is shown in Table 20-2. DOE values are 40 percent of those shown in the table.
9. Where the gas pipeline workpad passes over belowground TAPS, stress calculations will be performed to verify the minimum cover requirements to maintain the integrity of TAPS. These stress computations will be in accordance with Alyeska criteria and design procedures.

[1] For purposes of stress calculations only. This represents the pipe temperature when the pipe becomes fully restrained by the soil. May be varied in final design.

20.3.3.8 Load Combinations

Design loads occurring simultaneously will be combined and the resulting stresses and strains will be limited in accordance with the design criteria specified this section. Loading combinations that will be analyzed are outlined in Figures 20-1, 20-2 and 20-3.

20.3.4 Stress-Strain Relationships

20.3.4.1 Biaxial Stress-Strain

A high-pressure gas transmission pipeline is in a state of plane stress. For a pipeline with loading in only one plane the state of stress is reduced to a biaxial stress condition.

Elastic-plastic analysis of the buried pipeline is based upon application of the von Mises Criterion. This criterion for biaxial condition is given as follows:

$$S_{eff} \text{ (von Mises Criterion)} = (S_h^2 - S_h S_1 + S_1^2)^{½}$$

Where:

S_{eff} = Maximum effective stress

S_h = Hoop stress

S_1 = Longitudinal stress

The Tresca Criterion is used for elastic analyses when considering operating loads and is given as follows:

$$S_I \text{ (Tresca Criterion)} = \text{Max. } [\,|(S_h - S_1)|,\ |S_h| \text{ or } |S_1|\,]$$

Where:

S_I = Maximum stress intensity

20.3.4.2 Membrane Stresses

Membrane stresses are those stresses which are uniformly distributed across the cross section of the pipe wall thickness. Hoop membrane stress is induced by internal pressure; and longitudinal membrane stress is induced in a buried pipeline by internal pressure, differential temperature, and seismic ground motion.

20.3.4.3 Bending Stress and Strain

Bending of the pipeline will induce bending stresses and strains in the pipe wall. The strains are assumed to vary linearly from a maximum compression to a maximum tension through the diameter of the pipe. In the elastic range, the corresponding stress also varies linearly. In the inelastic range, the bending stress distribution is nonlinear.

20.3.5 Nonlinear Analyses For Buried Pipe

20.3.5.1 General

The nonlinear analyses will be performed on the buried pipe in order to consider the effects of secondary stress and strain produced by geotechnical conditions.

The purpose of the nonlinear analysis is to provide a more realistic representation of structural behavior to determine either load-deformation or load-strain relations for the structure and/or its individual elements. Nonlinear analyses are based upon an idealization of actual material properties. The analyses are complex mathematical models requiring the use of computer programs. The steel stress-strain relationship, as given by a representative stress-strain curve, is a basic input required for completing these computations. Figure 20-4 shows a representative stress-strain curve for the design material. The curve was determined using the specifications for steel pipe and representative longitudinal tensile stress-strain curves for API-5LX/5LS, Grade 80 pipe.

Studies will be conducted to investigate pipe stress and strain under anticipated design loading conditions and soil response. For design, the soils will be classified as outlined in Section 20.

The objective of the studies will be to determine the limits of pipe displacement and deformation allowed by the criteria limits. Via the analysis, pipe curvature changes occurring under design loadings can be related to the strain levels.

The results of the studies will be used to develop the following tools for the final design:

- Design charts representing the maximum allowable pipeline bend angles versus the depth of cover over the pipe.
- Design charts representing allowable differential soil settlement based on depth of burial of the pipe.
- Design charts for determining ditch modes for areas susceptible to frost heave.
- Analysis of site specific geotechnical concerns.

20.3.5.2 Input Models for Pipe Stress Analysis

The accuracy of the results from a pipe stress computer analysis is dependent upon the techniques used in preparing the program input. A suitable procedure for input modeling is discussed below.

In order to perform a computer analysis, four categories of input to the program are required:

- Geometrical Configuration
- Material Properties of the Pipe
- Soil Resistance Properties
- Loading Conditions

The geometrical configuration is idealized by representing a section of pipe which is divided into a number of members.

Pipe material properties will be input by specifying a series of data points on the stress vs. strain curve, a value for Poisson's ratio, and the-coefficient of thermal expansion. The pipe diameter and wall thickness will also be specified.

Soil restraint is represented as a series of discrete functions acting along the discrete members within the analysis model. For example, transverse soil restraining functions may be represented by a multi-linear force- displacement function.

Four types of loading will generally be appropriate. They are: variation in pressure, temperature load, settlement and frost heave. The computer program combines the applied loads in a particular sequence as specified by the user. Each load step is considered a continuation from the previous load step; the stresses, strains, loads, and displacements at each element will be given at the end of each load step.

20.3.5.3 Three-Dimensional Effects

Basically the gas pipeline is considered to lie in a single plane in finite sections sufficiently long to be analyzed independently in a two-dimensional design analysis. For these conditions, the significant dynamic loads caused by earthquakes may be represented as equivalent axial static temperature loads. Certain site-specific areas or special designs may require the consideration of a three-dimensional configuration and/or dynamic loading.

The single plane configuration will be subject to out-of-plane (3-D) loading due to vertical displacement at sidebends. A complete evaluation requires a three-dimensional analysis for each combination of loading conditions. Such an analysis will be performed by the ANGTS pipe stress computer model.

20.3.6 Bend Analysis

20.3.6.1 General

As the gas pipeline traverses the specified route, changes in gas pipeline alignment, terrain, grade elevation, and ditch conditions dictate that field bends will be required. These field bends will be made by means of bending machines. For practical purposes, and in order to prevent wrinkling or other damage to the gas pipeline, a 48-inch diameter pipe will be bent to a minimum radius of curvature of 120 feet (minimum radius of factory bends will be 20 feet).

When a bent section of pipe is subjected to loading, such as hydrostatic test pressure, operating pressure, variations in temperature, seismic loading etc., straining of the pipe will occur, and the pipe will tend to be displaced from its original position. This pipe displacement will be resisted by the stiffness of the pipe, the longitudinal restraint between the soil and pipe, and the transverse soil resistance. For geotechnical concerns, see Section 20.

Limits are placed on the permissible amount of transverse displacement and axial straining at a bend. These limits are checked by conducting elastic-plastic analyses of bends using the pipe stress computer program. From these analyses, restrictions on the maximum amount of bending are determined. This method of analysis and its application are discussed below.

20.3.6.2 Input Parameters for Computer Analysis

To perform a bend analysis using the ANGTS computer program, four categories of input to the program are required:

- Geometrical Configuration of the Bend
- Material Properties of the Pipe
- Soil Resistance Properties
- Loading Conditions

The geometrical configuration of a bend is idealized by dividing a section of pipe into a number of segments which are further subdivided into a specified number of equal members. For a single bend, an axis of symmetry exists at the apex of the bend and thus only half the bend needs to be analyzed. Load transfer between the two halves of the bend is simulated by axial and rotational restraint at the centerline of the bend. For multiple bends where no axis of symmetry exists, the total bend configuration is modeled.

20.3.6.3 Basis for Design

For bend analyses, both strain and displacement are checked against the governing criterion to determine the maximum bend angle in a particular soil as outlined below:

The allowable axial strain criteria for straight pipe are given in Subsection 20.2. The effect of cold straining the pipe during the field bending process has been considered in determining the applicability of these criteria for bend design. Cold bending alters the stress-strain properties at the extreme fibers of the pipe cross section. [For the inside fiber of a bend, the axial stress-strain relationship is essentially elastic for an increase in compressive strain whereas, for the outside fiber, the axial stress-strain relationship is softer (has lower proportional limit) than that for straight pipe.] These changes in stress-strain relationship are automatically accounted for in the computer analysis. The action of closing a bend, that is, imposing a greater curvature on a field bent section of pipe induces wrinkling in the pipe at a lower level of axial compressive strain increment, "but at a higher increment of axial stress,'" than the level for straight pipe. Thus, the allowable compressive axial strain increment for the action of closing a field bent section of pipe is reduced by 20% and the design factors for the various loading combinations are applied to this value. The action of opening a bend, or reducing the curvature of a bend, induces wrinkling at a higher level of axial compressive strain increment, "but at a lower increment of axial stress," than for straight pipe. No limit is required for this condition because the axial tensile strain increment limit for straight pipe will control the design.

From a geotechnical standpoint, pipeline movement will be limited to ensure stability and predictability. Both the horizontal and vertical limits for unfrozen soils are set to ensure that the pipe will not experience loss of ultimate soil strength as it displaces. The displacement limits also minimize possible scoring of the pipe coating or excessive soil settlement.

The displacement limits for bends located in unfrozen soils are 12 inches for horizontal movement, 6 inches for vertical movement with 5 feet or less cover, or 12 inches for vertical movement with more than 5 feet of cover. Since these displacement limits are not determined by stress and strain conditions of the pipeline they may be reconsidered for reduction on a site specific basis based upon stress analysis. For vertical movement, the displaced soil strength will also be used. Thus, if the bend is initially installed with 7 feet of cover and the allowable displacement limit is 12 inches, then the soil strength at 6 feet of cover is used in the analysis.

20.3.6.4 Application of the Design Method

The bend design will apply to two broad categories of analysis: site specific investigations and general design applications. Site specific investigations include:

- Road Crossings
- River Crossings
- Foreign Pipeline Crossings
- Bridges
- Shop-fabricated Bends

For these analyses, the specific conditions at the site will be used to determine the computer input models. In addition, other design limitations may be imposed upon the design which will be specific to the particular analysis. Such limitations include allowable proximity to a foreign pipeline, minimum depth of cover at a river crossing, and allowable movement in the casing at cased road crossings.

The majority of the gas pipeline will be designed on a general basis not requiring site specific analyses. Computer analyses will be used to develop design charts relating allowable bend angle to depth of cover at a bend.

The discussion in Subsection 20.3.6.5 to 20.3.6.6primarily applies to the design of bends in unfrozen soils. For bends occurring in ice-rich, frozen soils this procedure is modified and this modification is given in Subsection20.3.6.8.

20.3.6.5 Single Bend Analyses

A single bend is a bend of constant radius of curvature, with the plane containing the bend being either the horizontal or vertical plane (bends that are inclined to these planes are combination bends and these are discussed separately). The bend may be contained in more than one joint of pipe and the inclusion of small sections of straight pipe within the bend are neglected in this definition.

To aid the design of single bends, design charts are developed for the analyses which give the allowable angle for various depths of cover depending on the following variables:

- Bend Mode
- Soil Type

- Water Table
- Installation Temperature Range
- Weighting
- Insulation

There are three different bend modes for single bends: sidebends, sagbends and overbends. A sidebend is a bend lying in a horizontal plane. Sagbends and overbends both lie in the vertical plane. A sagbend has the center of curvature located above the pipe. An overbend has the center of curvature located below the pipe.

Soil type is categorized based on the geotechnical characterization for bend design. The category defines soil class and soil density. A particular design chart may be defined for more than one soil class and for a range of soil densities. The density of soil to be considered in selecting a design chart depends upon the bend mode. For sidebends, the in-situ density will be used; for vertical bends, the final density of the backfill will be used.

The level of the water table affects bend design in two ways: (1) for all bend locations, soil with a high water table has less resistive strength than the same soil with a low water table and, (2) for vertical bend locations, a high water table produces a buoyant effect on the gas pipeline.

At certain locations, the pipeline will be weighted by either concrete coating or set-on weights. This will affect the allowable bend angle in the vertical direction. The design chart appropriate to the type and amount of weighting will be used.

On each chart the range of installation temperatures for which the chart is suitable will be specified. For vertical bends the design will also account for the possibility of a reduced backfill density if the backfill is frozen. This option will also permit the possibility of allowing a less restrictive bend design by considering a specific temperature range rather than the maximum possible temperature range.

Insulation affects the allowable bend angle in two ways: (1) insulated pipe effectively increases the amount of soil that is mobilized to resist movement, and hence, increases the total soil resistance for a given soil; and (2) insulated pipe exhibits a greater buoyant effect in high water table locations which reduces the allowable bend angle for vertical bends. The thickness of insulation will be indicated on the design chart where appropriate.

These charts are developed based upon the assumption that the soil is unfrozen. The mechanical properties of the insulation are such that it is much stiffer and stronger than the soil in the horizontal and upward directions for the range of values considered. If the insulation properties were combined with those of the soil, the soil resistance values would not change significantly. Thus, the insulation properties do not have to be considered in the analyses.

These charts are to be used in developing comprehensive and practical specifications for applying bend limitations to the pipeline alignment. These specifications may be in the form of generalized statements such as "The minimum cover requirement at all overbend locations is X feet; the maximum permissible overbend angle is Y degrees", or they may be in the form of a chart which relates maximum allowable bend angle to the depth of cover for a particular set of conditions. The final form of these specifications will be determined when project needs and procedures are established.

20.3.6.6 Combination-Bend Design Analyses

A combination bend is defined as a plane bend that occurs in a plane which is inclined to the horizontal and vertical planes. A combination bend may be considered as a single bend where the soil restraint is not equal to either the uplift or lateral soil strength, but is a combination of these values. This inclined soil strength is dependent upon the ratio of uplift to lateral soil strength for a particular soil type, and upon the angle of inclination of the combination bend. The use of this inclined soil strength allows a combination bend to be treated as an equivalent single bend and thus the allowable angle for a set of design conditions may be determined.

20.3.6.7 Adjacent Bend Design Analyses

Three types of adjacent bends are defined:

- Out-of-plane bends - two bends that do not lie in the same plane (e.g., side-sag).
- Reverse bends - two bends in the same plane, but in opposite directions (e.g., sag-over)
- Multiple bends - two or more bends in the same plane and in the same direction (e.g., sag-sag).

Out-of-plane bends require no special procedure. They will be treated as two single bends using the single bend design methodology outlined previously.

For the other two cases, a modification to the single bend procedure is used. This modification of the approach is based on the length of separation of the bends and the resisting soil strength.

For multiple bends a separation length is determined, which is a function of the soils' ultimate resistance. At this length, the two bends influence on each other with regard to strain and displacement is negligible and the two bends are treated individually. For values of separation less than this length, the two bends will influence each other producing greater bend movement than for a single bend analysis. The amount of influence depends on the actual separation length. This influence will be taken into account in developing specifications for multiple bends.

For reverse bends, a similar procedure is used.

20.3.6.8 Design of Bends in Frozen Soils

At some locations, the gas pipeline will pass through frozen ice- rich soils which may deform excessively under long-term sustained loads. At such locations, the previously outlined procedure for the analysis of bends in unfrozen soils will not necessarily represent a conservative design. For these conditions the effect of long-term loading in frozen soils will be investigated. However, for frozen ice-poor soils, the procedure developed for unfrozen soils will be used, assuming that these soils will be allowed to thaw.

The significant difference between bend design in frozen soils from that for unfrozen soil is in the representation of the soil support. Soil functions describing the long term frozen strength and displacement rate under sustained are dependent upon the soil temperature.

Analyses, using the pipe stress computer code, will be performed using these soil functions to determine a critical temperature at which there is no restriction of the allowable bend angle. For locations where the soil temperature is below the critical value no special restrictions are imposed upon the design of bends. For temperatures that are above the critical value, allowable bend angles will be defined for each soil temperature range.

The allowable bend angles for these frozen soils will be determined by limiting the allowable axial strain in the pipe. If it is required that larger angles than the allowable angle be made, then the surrounding soil will be over excavated and replaced with a thaw stable material and the bend restrictions for unfrozen soil will apply.

This design does not apply to movement in the vertically upward direction because ice-rich materials will not be used as backfill at bend locations.

20.3.7 Settlement Analysis

A buried pipeline is essentially continuously supported by the ditch bottom. It is recognized, however, that certain geotechnical conditions could cause vertical movement of the supporting soil. Terrain disturbance occurring during construction may cause thawing of the permafrost and induce some settlement prior to operation and the creation of a frost bulb. For short sections, the pipe will be able to span the settled soil regardless of the amount of settlement without exceeding the design criteria. For longer spans, it will be necessary to determine the amount of differential settlement which may be allowed. The vertical displacement of the pipe will be resisted by the stiffness of the pipe, by the strength of the supporting soil on each side of the span of settlement, and by the longitudinal restraint provided by the soil. For geotechnical concerns see Section 20.

The pipe stress computer program is used to conduct nonlinear analyses of regions of settlement. From such analyses, the amount of allowable settlement is determined by limiting the amount of axial straining in accordance with the allowable strain criteria.

Settlement studies may be performed at specific locations, such as certain well-defined thaw unstable regions. The majority of the pipeline, however, will traverse areas where accurate information about settlement span cannot be specifically determined. This method is outlined below:

- Classify the design cases into "Settlement Soil Groups" based upon combinations of end conditions, soil types outside the zone of settlement and soil types within the zone of settlement.
- Determine the soil load displacement functions for each selected soil group for a range of cover depths and a range of frost bulb weights.

- Develop the input models for a computer analysis for a range of spans for the selected soil groups, depths of cover and frost bulb weights.
- Perform analyses for the range of settlement spans for each combination of soil group, depth of cover and frost bulb weight. The allowed settlement for each span is the settlement at which the allowable pipe strain is reached.
- Plot a relationship between allowable settlement and span for each soil group, depth of cover and frost bulb depth.
- Determine the critical span at which the allowable settlement will be at minimum from this relationship and determine the allowable settlement at the critical span. This will be the total allowable settlement, independent of span, for a given soil group and depth of cover.

From these analyses, settlement design charts will be developed identifying the allowable settlement for each soil group at each depth of cover for straight pipe and for a range of bend angles. The values obtained from the chart will be compared to the predicted amount of settlement along the pipeline alignment. Thus areas where mitigation is required will be identified.

20.3.8 Other Geotechnical Considerations

20.3.8.1 Differential Soil Displacement

At certain locations along the pipeline, additional geotechnical conditions may exist that will cause displacement of the soil around the pipe, such as displacement of the soil due to differential slope movement.

At any location where differential soil displacement may occur, the soil movement will have the effect of inducing a loading action on the pipe, the magnitude of these induced forces being a function of the amount of movement and the soil properties. Depending on the nature of the phenomenon, these displacements may be any combination of transverse movement, (producing bending of the pipe) or axial movement (producing a tension-compression effect in the pipe). All design cases of soil displacement will be analyzed using an appropriate non-linear procedure.

In an analysis, the soil movement is represented as a displacement of the soil springs as described for settlement. Both transverse and axial movements may be represented. The results from these analyses will be compared with the strain criteria. The analysis will follow the two-stage procedure outlined below:

1. Soil load-displacement characteristics for the displacement of the pipeline in relation to the soil will be determined.
2. Pipeline strains will be calculated for each problem incorporating the following behavior phenomena:

- Soil Behavior
- Pipe Material Behavior
- Internal Pipe Pressure
- Differential Temperature Stresses

At locations where the predicted strains exceed the allowable strain levels, a design will be developed to reduce the level of straining to an acceptable level.

20.3.8.2 Seismic Liquefaction

Certain soils along the pipeline may be subject to the development of high pore pressures during earthquake activity. As a result, differential soil displacement may occur on slopes due to slide movement or slope failure. Design cases for these conditions are analyzed as outlined above.

Should liquefaction of soils occur on level ground, the pipe will be subjected to an upward buoyant force due to the higher density of the liquefied soil, and then the pipe will tend to float to the ground surface. This will induce bending stresses and strains in the pipe due to the restraint of the adjacent non-liquefied soil. For certain extreme, unpredictable and indeterminate soil conditions, the stress and strain levels may exceed the limit values specified in the criteria. This however, is not likely to cause rupture of the gas pipeline, since the specified criteria limits only predict incipient localized wrinkling or buckling. The pipe is capable of undergoing deformations many times larger than those specified by the limits prior to failure, and the maximum pipe displacement is limited to that required for the pipe to reach the ground surface. Therefore, generally the pipeline will not be specifically designed to resist the effects of seismic liquefaction on level ground.

20.3.8.3 Frost Heave Analysis

Frost heave causes vertically upward movement of the supporting soil under the pipe. Analogous to the settlement analysis, it is necessary to analyze a range of frost heaving spans between lesser heaving segments to determine which span will be the most restrictive on design. The vertical displacement of the pipe will be resisted by the stiffness of the pipe and by the resistance of the soil above the pipe.

The pipe stress computer program is used to conduct nonlinear analyses of regions of frost heave. From such analyses, the allowable ditch burial mode is determined by limiting the amount of axial strain in accordance with the design criteria established in Section 20.

20.3.9 Aboveground (A/G) Pipeline

Specific locations along the pipeline will require an elevated design mode. This condition is expected to be encountered at certain river crossings, and compressor/metering station interfaces.

Only elastic methods of analysis and design will be considered. Operating dead load, snow/ice load, wind load, earthquake loads, test loads, and thermal loads will be applied to the pipe and its support system, and load combinations as referenced in Figure 20-3 will be considered. Earthquake response spectra will be used for the pipeline analysis. These spectra and design criteria will be established for the specific application to aboveground pipeline. Both the Design Contingency Earthquake and Design Operating Earthquake will be considered for each of the three zones defined in the design criteria. The effects of wave propagation over long segments of aboveground pipeline will be considered, and in transition zones where the pipeline will change from the above- ground to the buried mode without an anchor, sufficient length of buried pipe will be considered to provide a virtual anchor.

The design of the pipe support and its foundation will be completed in accordance with the applicable referenced codes and standards. The appropriate allowable stresses for the structural materials used will be determined from the respective codes. For steel structures, these values will be obtained from the AISC code; for concrete structures they will be obtained from ACI-318. Allowable stresses for the pipe will be in accordance with the criteria of this section and Figure 20-3 for the given load combinations. Foundation design will be established on a site-specific basis.

Pipe support spacing will be determined to minimize the bending forces imposed on the pipe by the operating dead load, live load (including pig weight) and earthquake load. Maximum allowed pipe deflection will be determined on a site-specific basis. Anchor point locations will be determined so that the pipe will not be overstressed and pipe displacement will be limited when the thermal and earthquake loads are applied.

The analysis and design of the pipeline at major aerial crossings will be coordinated with site specific analysis and design of the structure.

20.4 FIGURES AND TABLES

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	Combinations										
Loads	1	2	3	4	5	6	7	8	9	10	11
Design Pressure	X	X	X	X	X	X	X	X			X
Test Pressure									X		
Zero Gage Pressure										X	
Operating Temperature Differential		X	X	X	X	X	X	X			
Test Temperature Differential									X		
DCE Buried Pipe				X			X	X			
DOE Buried Pipe			X								
Overburden					X		X		X	X	X
Wheel Loads					X		X		X	X	X
Buoyancy						X		X			
Allowable Stress Criteria	**A**	**B**	**C**	**D**	**C**	**C**	**F**	**F**	**G**	**E**	**E**

A. Hoop Stress per 49 CFR 192

B. 0.9 SMYS, Maximum Stress Intensity

C. 1.0 SMYS, Maximum Stress Intensity

D. 1.1 SMYS, Maximum Stress Intensity

E. 0.9 SMYS, Maximum Hoop Bending Stress+Pressure Hoop Stress

(0.8 SMYS, at uncased road crossings)

F. 1.15 SMYS, Maximum Stress Intensity

G. 1.10 SMYS, Maximum Effective Stress

Figure 20-1 Load Combinations of Elastic Analysis of Buried Pipe

	Combinations							
Loads	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Design Pressure	X	X	X	X	X	X		
Test Pressure							X	X
Operating Temperature Differential	X	X	X	X	X	X		
Test Temperature Differential							X	X
DCE Buried Pipe				X	X	X		
DOE Buried Pipe	X	X	X					
Settlement	X			X			X	
Bend Movement	X	X	X	X	X	X		X
Frost Heave			X			X		
Buoyancy		X			X			
Dead Load	X	X	X	X	X	X	X	X
Allowable Stress Criteria	**A**	**A**	**A**	**C**	**C**	**C**	**B**	**B**

A. Based on Maximum Allowable Longitudinal Strain, Compressive and tensile

B. Based on Maximum Allowable Longitudinal Strain, Compressive and tensile

C. Based on Maximum Allowable Longitudinal Strain, Compressive and tensile

Figure 20-2 Load Combinations of Inelastic Analysis of Buried Pipe

	Combinations							
Loads	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Design Pressure	X	X	X	X	X	X		
Test Pressure								X
Operating Temperature Differential		X	X	X	X		X	
Test Temperature Differential								X
Dead Load Operation		X	X	X	X	X		
Dead Load Test								X
DCE Aboveground Pipe				X				
DOE Aboveground Pipe			X					
Wind		X			X	X	X	
Snow/Ice		X	X	X	X	X		
Allowable Stress Criteria	**A**	**A**	**A**	**C**	**C**	**C**	**B**	**B**

A. Hoop Stress per 49 CFR 192

B. 0.9 SMYS, Maximum Stress Intensity

C. 1.0 SMYS, Maximum Stress Intensity

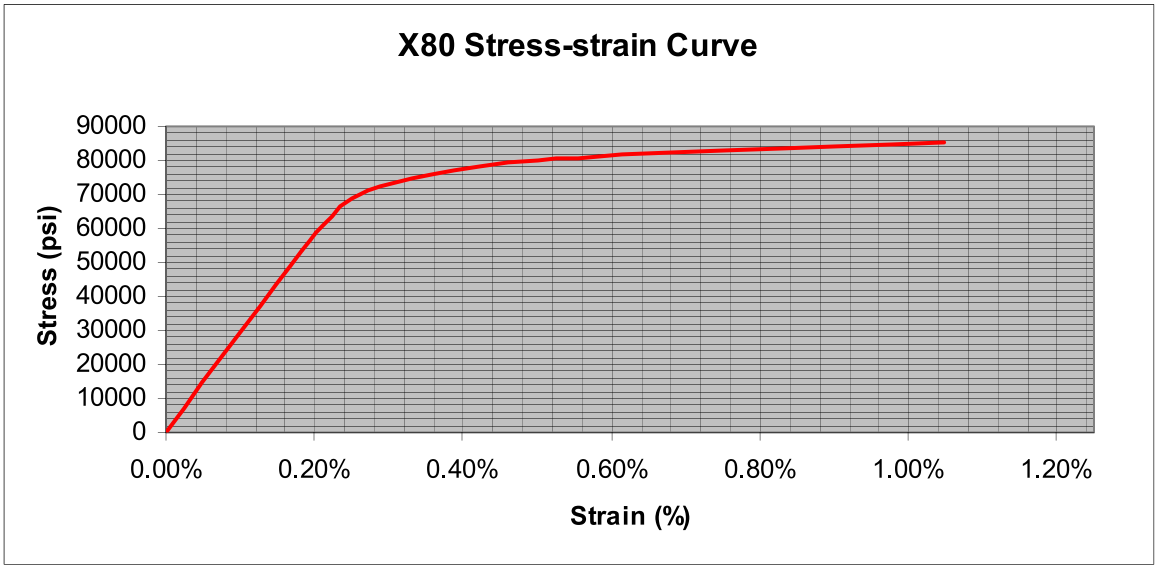
D. 1.1 SMYS, Maximum Stress Intensity

E. 0.72 SMYS, Maximum Stress Intensity

F. (F) (0.75 SMYS), Maximum Longitudinal Stress
(F = Design Factor from 49 CFR 192)

G. 1.10 SMYS, Maximum Longitudinal Stress Combined with Torsional Stress

Figure 20-3 Load Combinations of Elastic Analysis of Aboveground Pipe



X80 Pipe material

Using Ramberg- Osgood equation: $\varepsilon = \sigma/E + \varepsilon_{py} (\sigma/F_y)^n$

where:

ε = strain (in/in)

σ = stress (psi)

ε_{py}= 0.005-F_y/E

F_y = yield stress (SMYS) = 80,000 psi

E = Modulus of Elasticity = 29,000,000 psi

n = non-dimensional exponent = 18, for this example curve

Figure 20-4 Example Longitudinal stress-strain curve for steel pipe

			Acceleration (g)			Displacement (g)			Velocity (in/sec)		Strong Motion
Zone	Location	Magnitude	Rock	Sediment	Soft Soil	Rock	Sediment	Soft Soil	Rock	Soil	Duration (sec)
I	Prudhoe Bay to 67°N	5.5	0.15	0.15	0.15	5	5	5	7	7	10
II	67°N to Big Delta	7.5	0.50	0.45	0.40	15	26	29	22	30	20
III	Big Delta to Canadian Border	7.0	0.40	0.35	0.30	11	16	19	17	19	15

Table 20-1 Effective Horizontal Ground Motion to Determine Buried Pipeline Response for Design Contingency Earthquake

			Acceleration (g)			Displacement (g)			Velocity (in/sec)		Strong Motion
Zone	Location	**Magnitude**	**Rock**	**Sediment**	**Soft Soil**	**Rock**	**Sediment**	**Soft Soil**	**Rock**	**Soil**	**Duration (sec)**
I	Prudhoe Bay to 67°N	5.5	0.15	0.15	0.15	5	5	5	7	7	10
II	67°N to Big Delta	7.5	0.50	0.45	0.40	15	26	29	22	30	20
III	Big Delta to Canadian Border	7.0	0.40	0.35	0.30	11	16	19	17	19	15

Table 20-2 Effective Horizontal Ground Motion to Determine Structural Response of Aboveground Pipeline and its Supports for Design Contingency Earthquake